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EFFECTS OF AIR CONTAMINATION IN A HELIUM TUNNEL

By Arthur Henderson, Jr., and Frank E. Swalley

Langley Research Center
Langley Field, Va.

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SUMMARY

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The effects of contamination of helium by air upon static-pressure, total-pressure, heat-transfer, and temperature measurements have been investigated in the 2-inch helium tunnel at the Langley Research Center. Within the scope of the tests, even a small amount of air is shown to affect these measurements. The heat-transfer and temperature measurements were made on a 26.6° half-angle cone and demonstrated the effects of contamination qualitatively. The wall static and center-line pitot pressures show that if the contaminating air is held to less than about 0.2 percent by volume, the error in indicated Mach number is less than 1 percent as calculated from the Rayleigh pitot equation. The corresponding errors in wall static and center-line pitot pressures are about 1.7 and 0.4 percent, respectively.

INTRODUCTION

The problem of condensation in wind tunnels is not new. Supersonic air tunnels have to maintain a low dewpoint in order to avoid the effects of condensation of water vapor as the air expands in the nozzle, with the accompanying decrease in static temperature and partial pressure of the vapor. Hypersonic air tunnels, in addition to maintaining a low dewpoint, must use preheated air in order to avoid condensation of a portion of the air itself. (See, for example, ref. 1.)

The use of helium in wind tunnels in order to avoid condensation of a portion of the test medium is well known. Mach numbers on the order of 30 are obtainable without preheat. Unfortunately, liquefaction of a portion of the helium itself is not the only condensation problem involved in helium-tunnel operation (as pointed out in ref. 2), although it would be if the helium used in the tunnel remained as pure as originally produced by the Bureau of Mines. As it comes from the production process, the helium contains at most 0.005-percent impurity by volume. This impurity consists almost entirely of hydrogen, nitrogen, and neon. (See ref. 3.)

After the helium leaves the producer, however, it is subject to contamination every time it is handled (transportation, distribution, pumping into smaller containers, etc.); and in a closed-cycle helium tunnel, contamination of the helium by air and thus by water vapor as well is inevitable, since the test section must be filled with air each time the model is changed or worked on. Also there is always the possibility of leaks in the joints or valves in the parts of the tunnel circuit which are at less than atmospheric pressure (nozzle, test section, diffuser, vacuum sphere, vacuum pumps, etc.).

The removal of contaminants such as water and oil is relatively straightforward. The removal of air is difficult, since low temperatures are required for its condensation.

When the helium expands to hypersonic Mach numbers, its static temperature and the partial pressure of any contaminating air present will, for the most part, be well within the region of condensation for air, as is illustrated in figure 1. This figure presents a portion of the static-pressure—static-temperature history of helium as it expands to hypersonic Mach numbers in a nozzle. Shown also in this figure are the vapor-pressure curves for helium, nitrogen, and oxygen (refs. 4 and 5). Thus, air presents the same problem in helium tunnels that water vapor does in supersonic air tunnels, and a purifier designed primarily to remove air from the helium must be an integral part of any closed-cycle helium tunnel. However, since no presently available helium purifier is 100 percent efficient, some air will always be present in the helium used for aerodynamic testing.

The main objection to condensation of air in a helium tunnel is that, as the air condenses, it gives up energy to the surrounding helium (besides loading the helium stream with liquid-air droplets and solid-air particles). Thus, as the helium flows through the nozzle, it carries with it an energy source which continually changes the properties of the helium as it expands in the nozzle. (Note that, although the present discussion pertains to the condensation of air in helium, it is generally applicable to any two gases with different vapor-pressure curves.)

The purpose of the present investigation is to determine the effects of contamination of helium by air, the aim being to establish approximate limits below which contamination effects are negligible as far as the use of helium as a hypersonic test medium is concerned. An equation is determined from measurements of wall static and center-line pitot pressures by which the maximum allowable amount of contaminating air can be numerically calculated. Results of heat-transfer and temperature distribution tests are also presented and show the effects of contamination in a qualitative manner only.

SYMBOLS

c_M	specific heat of model skin
h	film coefficient of heat transfer
l	axial length of cone from nose to base
M	Mach number
p_a	partial pressure of air component of mixture
p_h	partial pressure of helium component of mixture
p_m	combined pressure of air-helium mixture
$p_{t,1}$	stagnation pressure
$p_{t,2}$	pitot pressure behind normal shock
p_w	tunnel-wall static pressure
$r = \frac{p_a}{p_h}$	contamination ratio
s	distance along cone surface measured on ray from nose
t	model-wall thickness
T_a	temperature of air
T_i	initial model-wall temperature at start of test
T_M	model-wall temperature
T_m	temperature of air-helium mixture
T_r	recovery temperature
$T_{t,1}$	stagnation temperature

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x — longitudinal distance in tunnel, measured from throat

γ — ratio of specific heats of gas

ϵ — percent error in M

ρ_M — density of model material

τ — time

Subscripts:

$0,1,2,3,\ldots n$ — denotes a particular mixture of a series of mixtures, each with a different r (except subscripts 1 and 2 when used with p_t)

Prime over symbol denotes that a quantity has changed but at constant r.

APPARATUS

The tests were performed in the 2-inch helium tunnel at the Langley Research Center. This tunnel is described in reference 6. A schematic of the test setup is presented in figure 2(a) which shows the 3,000-lb/sq in. 12-cubic-foot mixing tank in which known amounts of air and helium were mixed. The mixing tank and the stagnation chamber were each equipped with a pressure gage and a thermocouple.

The model used in the heat-transfer and temperature distribution tests was a 26.6° half-angle cone with a base diameter of 3/8 inch. The cone was constructed by electroforming nickel on a steel mandrel and then machining to a wall thickness of 0.010 inch. The four thermocouples were made of No. 36 chromel-alumel wire and were located at $s/l = 0.259$, 0.554, 0.782, and 1.005.

For the heat-transfer tests, a temperature difference between the model and the free stream was required. This condition was accomplished by cooling the model and heating the mixture. A 0.090-inch-diameter tube, with a fine pattern of small holes along the end, was located inside the model. It acted as a duct for pressurized carbon dioxide which upon escaping, expanded and cooled the model. A steam heat exchanger raised the temperature of the helium-air mixture to about 230° F before it reached the stagnation chamber. The stagnation chamber and the piping between the stagnation chamber and the heat exchanger were preheated prior to a test to insure a constant stagnation temperature.

To obtain a step input of heat transfer, a quick start of the tunnel was used. A plunger-type plug located in the stagnation chamber sealed the nozzle entrance. It was operated by a steel rod which extended through the chamber wall. The actual seat was made by a ring of soft solder placed on the face of the plug. The plug itself was cylindrical and machined out of steel. Just prior to a test, the plug was seated, and all the valves between the stagnation chamber and the mixing tank were opened. "Popping the plug" started the tunnel. A diagram of the system is shown in figure 2(b).

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Stagnation and mixing-tank pressures were measured on Bourdon tube gages with a maximum error of ±1.0 percent of the measured pressure. A compound gage with an accuracy of ±0.4 percent of the measured pressure was used to record the pitot pressures. The wall static pressures were measured on U-tube butyl phthalate manometers to an accuracy of ±0.01 inch of butyl phthalate. Stagnation and mixing-tank temperatures were measured by thermocouples whose output was connected to self-balancing potentiometers. Time-temperature histories on the cone were recorded on multichannel oscillographs during the temperature and heat-transfer distribution tests.

TESTS

In this series of tests the parameter which is used to describe the amount of contamination present is r, the ratio of the number of air molecules to the number of helium molecules which, for gases obeying Avogadro's law, is the ratio of their partial pressures. The method by which various values of r were obtained for these tests is given in the appendix.

The effects of contamination were determined on tunnel-wall static and center-line pitot pressure measurements and on the temperature and heat-transfer distribution tests on a 26.6° half-angle cone at $(M)_{r=0} = 19$.

At any partial-pressure ratio, the effect of contamination at any point in a nozzle will depend upon both the stagnation temperature and the stagnation pressure, since these quantities control the local values of static temperature and static pressure. Figure 1 shows that the condensation properties of air (oxygen and nitrogen curves) are a much stronger function of temperature than of pressure and that condensation problems increase with decreasing temperature. Consequently, the wall static-pressure tests were conducted with stagnation temperatures close to ambient, which are generally the lowest met with in wind-tunnel practice, and should give conservative results. It was not considered necessary to vary stagnation pressure, since even an order of magnitude change in pressure has little effect on the condensation temperature. Thus, a single stagnation pressure of 1,015 lb/sq in. abs was used during these tests.

The stagnation temperature was increased to about 230° F for the heat-transfer and temperature distribution tests; the stagnation pressure was increased to 1,515 lb/sq in. abs because the tunnel would not start with the 26.6° half-angle cone in it with $p_{t,1} = 1{,}015$ lb/sq in. abs.

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RESULTS

Pressure Distribution

Figure 3 presents the variation of the wall static-pressure ratio $p_w/p_{t,1}$ with the contamination ratio r for tunnel stations $x = 2$ to 6 inches at $p_{t,1} = 1{,}015$ lb/sq in. abs. Data were also obtained at stations $x = 8$ to 11 inches (tube at $x = 7$ in. was obstructed) but are not presented, because they were affected by the shock which was caused by the juncture of the conical nozzle and the cylindrical test section. The curves are all nearly parallel and are well represented by

$$\frac{p_w}{(p_w)_{r=0}} = e^{8.5r} \tag{1}$$

Thus, within the scope of these tests, it can be seen that any amount of air contamination will affect static-pressure measurements in helium flow. Also, the effects of the contamination on static pressure are independent of Mach number in the test range ($M \approx 7$ to 14).

A check on the variation of the center-line pitot pressure at stations $x = 3$ and 11 inches is presented in figure 4 and shows that within the range of these tests $p_{t,2}$ is relatively insensitive to r. The results are also independent of M in the test range ($M \approx 9$ and 18) and can be approximately represented by

$$\frac{p_{t,2}}{(p_{t,2})_{r=0}} = e^{-2r} \tag{2}$$

If the wall static pressure is assumed to represent closely the center-line static pressure, then the Rayleigh pitot formula may be used to establish a permissible upper limit on r. The Rayleigh equation is here written

$$\frac{p_{t,2}}{p_w} = \left[\frac{(\gamma + 1)M^2}{2}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{\gamma + 1}{2\gamma M^2 - (\gamma - 1)}\right]^{\frac{1}{\gamma-1}} \tag{3}$$

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When $M^2 \gg 1$, this equation can be solved for M and is given very accurately by

$$M \approx \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{2}}\left[\frac{4\gamma}{(\gamma + 1)^2}\right]^{\frac{1}{2(\gamma-1)}}\left(\frac{p_{t,2}}{p_w}\right)^{\frac{1}{2}} \tag{4}$$

which for helium ($\gamma = 5/3$) becomes

$$M \approx 0.825\left(\frac{p_{t,2}}{p_w}\right)^{\frac{1}{2}} \tag{5}$$

The percent error incurred by using equation (5) rather than equation (3) is as follows:

M	Percent error
1	18.2
2	3.9
3	1.7
4	0.95
5	0.50
10	≈0

Substituting equations (1) and (2) in equation (5) gives

$$M = 0.825\left[\frac{\left(p_{t,2}\right)_{r=0}e^{-2r}}{\left(p_w\right)_{r=0}e^{8.5r}}\right]^{\frac{1}{2}} = \frac{(M)_{r=0}}{e^{5.25r}} \tag{6}$$

If it is specified that r be such that no more than ϵ percent error be incurred in the indicated Mach number, then

$$100 \frac{(M)_{r=0} - M}{(M)_{r=0}} = \epsilon \tag{7}$$

Substituting equation (6) in equation (7) gives, finally,

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$$r = \frac{1}{5.25} \log_e \left(\frac{1}{1 - \frac{\epsilon}{100}} \right) \tag{8}$$

Expressing equation (8) in a series gives for $\frac{\epsilon}{100} \ll 1$

$$r = \frac{\epsilon}{525} \tag{9}$$

The permissible value of r is independent of Mach number, as would be expected, since the wall static and center-line pitot pressures were not dependent on Mach number for the ranges tested. It is felt that a permissible value of ϵ is 1 percent, for which case the maximum allowable value of r is on the order of 0.002. This ratio is equivalent to 0.2 percent by volume of air in the helium. However, this same contamination ratio of $r = 0.002$ would produce an error of 1.71 percent in wall static pressure and of 0.40 percent in center-line pitot pressure.

The qualitative effect of the contamination ratio r on the indicated Mach number is illustrated in figure 5 by use of the measured pressures at $x = 3$ inches. Indicated Mach numbers have been determined from the Rayleigh pitot equation (eq. 3) and from the isentropic flow tables of reference 7 with the use of the ratios $p_{t,2}/p_{t,1}$ and $p_w/p_{t,1}$. It is seen that none of the methods for predicting Mach number is in agreement except at $r = 0$. The trends are similar to the results shown in reference 1 for the condensation of air in a hypersonic air tunnel. The limiting value of $r = 0.002$ is denoted by a vertical dashed line. The dashed-line curve represents equation (6) and shows good agreement with the points which were calculated from the exact Rayleigh pitot equation.

Heat-Transfer and Temperature Distributions

Heat-transfer and temperature distribution tests were made on a 26.6° half-angle cone in order to show the effects of contamination on these quantities in a qualitative manner only at $(M)_{r=0} = 19$.

The thin-skin transient-temperature technique was used to obtain heat-transfer data. The heat-transfer equation (with the assumption that all the heat is stored and that conduction and radiation effects are negligible) is

$$\rho_M c_M t \frac{dT_M}{d\tau} = h\left(T_r - T_M\right) \tag{10}$$

and the solution for h is given by

$$h = -\rho_M c_M t \frac{d}{d\tau}\left[\log_e\left(T_r - T_M\right)\right] \tag{11}$$

Thus, a measure of the film coefficient of heat transfer is obtained by plotting $\left(T_r - T_M\right)$ against the time τ on semilog paper. Such a plot has been made in figure 6 for various values of r at several thermocouple locations s/l. Between the time it takes for constant flow conditions to be established on the model and the time at which skin conduction effects begin to predominate, the curves of this figure are approximately straight lines. The variations of the slopes of the straight portions of the curves of figure 6 with the contamination ratio are shown in figure 7. The slopes are in arbitrary units proportional to the heat-transfer coefficient. The effect of contamination is thus seen to increase the heat-transfer coefficient; that is, the slopes of the curves increase with increasing r.

Another interesting effect of contamination is the manner in which it affects the equilibrium temperature on a model. Actually none of the model tests were of sufficient duration for complete equilibrium to be established. Because of this fact and because no two runs were begun with the model at the same initial temperature, the effect of contamination on temperature distribution was determined by use of the parameter $\frac{T_M - T_i}{T_{t,1} - T_i}$. In each case, the T_M used was the value obtained 9 seconds after the test was started. Figure 8 presents this parameter against r

for several values of s/l. The most striking feature is that with enough contamination present, it is possible to attain temperatures on the model which are higher than stagnation temperature. (These temperatures are much greater than can be accounted for by the Joule-Thomson effect.)

Note that even very small amounts of contamination affect the heat-transfer and temperature measurements. A similar result was found from the wall static-pressure tests. The vertical lines at $r = 0.002$ mark the permissible contamination ratio as determined from the pressure tests for the condition that the error in indicated Mach number be no more than 1 percent.

Effect on Tunnel Starting

One of the interesting effects of contamination is its effect on starting flow in the tunnel. During the heat-transfer tests on the 26.6° half-angle cone, the tunnel became increasingly difficult to start as the ratio of air to helium was decreased. During the zero-contamination test, several attempts were made to start the tunnel before a successful run was obtained. This result suggests that contaminated helium might be used for the purpose of starting the tunnel in order to test models which are larger or blunter than could otherwise be tested. Some means must be devised for controlling the duration of flow of contaminated helium so that it lasts no longer than is necessary to establish flow (say, for the first 0.1 second), after which pure helium would be used for the remainder of the run. One means by which this could be accomplished is the plug-in-throat technique, used during the heat-transfer tests, with contaminated helium in the stagnation chamber. When the plug is withdrawn the initial charge of contaminated helium would be followed by pure helium.

Possible Use of Contaminated Flow

Because the phenomenon of dissociation and recombination of real nonmonatomic gases is somewhat analogous to a change of phase (evaporation and condensation), there is the possibility that contaminated helium might be used to simulate certain aspects of real-gas effects. However, a great deal of exploratory theoretical and experimental work would have to be done to evaluate the feasibility of such a concept.

CONCLUSIONS

The present tests have shown that any amount of air contaminating the helium used for wind-tunnel testing will affect static-pressure, heat-transfer, and temperature measurements, each of these measurements increasing with increasing ratios of air to helium. The center-line pitot pressure was relatively insensitive to contamination and showed only a slight decrease with increasing contamination. Practical limitations on the permissible amount of contamination can be established, however. For example, the wall static and center-line pitot pressures show that if the contaminating air is held to less than 0.2 percent by volume, the error in indicated Mach number will be less than 1 percent as calculated from the Rayleigh pitot equation. The corresponding errors in wall static and center-line pitot pressure are about 1.7 percent and 0.4 percent, respectively.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., March 28, 1960.

APPENDIX

DETERMINATION OF r

Before the initial mixture is prepared, the mixing tank is evacuated. The desired amount of air at a dewpoint of -55° F is then bled in, and its pressure $p_{a,0}$ and temperature $T_{a,0}$ are measured simultaneously. Next, pure helium is added, and the pressure $p_{m,1}$ and temperature $T_{m,1}$ of the mixture are measured simultaneously. Since the density of the air component of the mixture cannot change, the partial pressure of the air $p_{a,1}$ at the time that $p_{m,1}$ and $T_{m,1}$ are measured is

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$$p_{a,1} = p_{a,0}\left(\frac{T_{m,1}}{T_{m,0}}\right) \tag{A1}$$

The ratio r_1 is determined from

$$\frac{1}{r_1} = \frac{p_{h,1}}{p_{a,1}} = \frac{p_{m,1} - p_{a,1}}{p_{a,1}} \tag{A2}$$

Once the partial-pressure ratio is known, it remains fixed regardless of pressure or temperature changes, until more helium (or air) is added to the mixture (with the assumption that the gases obey Avogadro's law and the perfect-gas law, which is reasonable for the pressures, temperatures, and gases involved).

A test is made with $r = r_1$ after which the pressure $p'_{m,1}$ and temperature $T'_{m,1}$ of the mixture are measured simultaneously. The partial pressure of the air is then

$$p'_{a,1} = \frac{p'_{m,1}}{1 + \left(\frac{1}{r_1}\right)} \tag{A3}$$

More helium is added to the mixture and the pressure $p_{m,2}$ and temperature $T_{m,2}$ are measured simultaneously. The partial pressure of the air at the time that the pressure and temperature of the new mixture are measured is

$$p_{a,2} = p'_{a,1}\left(\frac{T_{m,2}}{T'_{m,1}}\right) \tag{A4}$$

The new partial-pressure ratio can be found from

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$$\frac{1}{r_2} = \frac{p_{h,2}}{p_{a,2}} = \frac{p_{m,2} - p_{a,2}}{p_{a,2}} \tag{A5}$$

A run is made with $r = r_2$, a new mixture is formed by adding more helium again, its value of r is calculated in like manner, and the same procedure is continued until the desired range of r has been covered.

It is interesting to note that if there is no change in temperature throughout the process and if the pressure of the mixture before each run is always p_m and after each run is always p'_m, then

$$\frac{1}{r_n} = \left(1 + \frac{1}{r_1}\right)\left(\frac{p_m}{p'_m}\right)^{n-1} - 1 \tag{A6}$$

where n is the number of the mixture for a particular run. This equation can be used to make a rough estimate of the number of runs necessary for any desired range of r.

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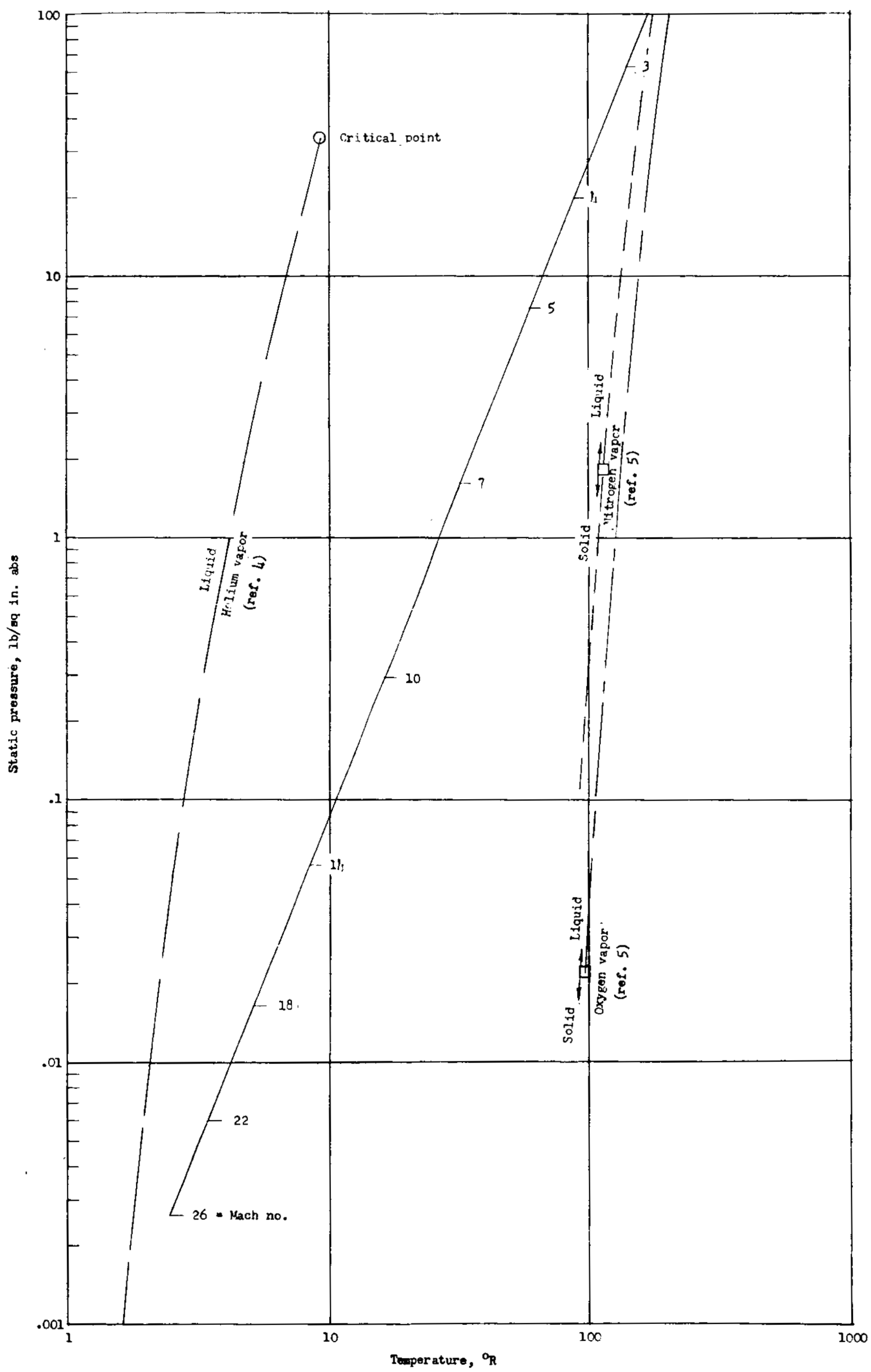
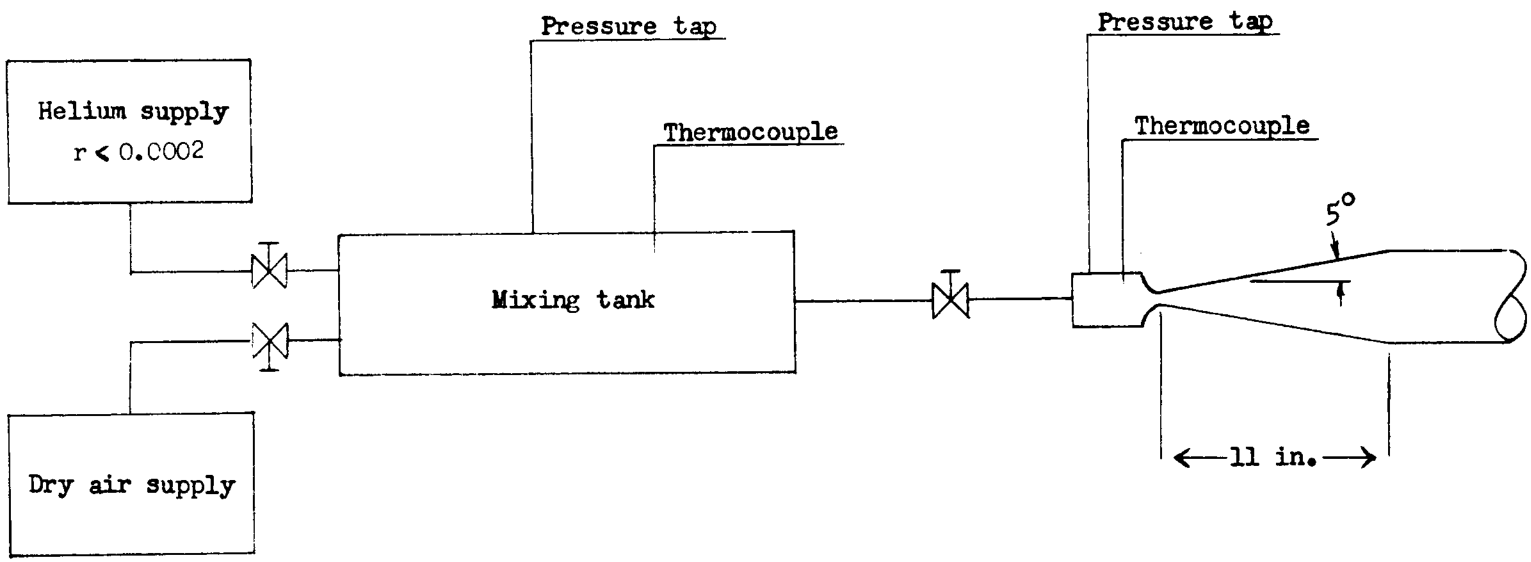
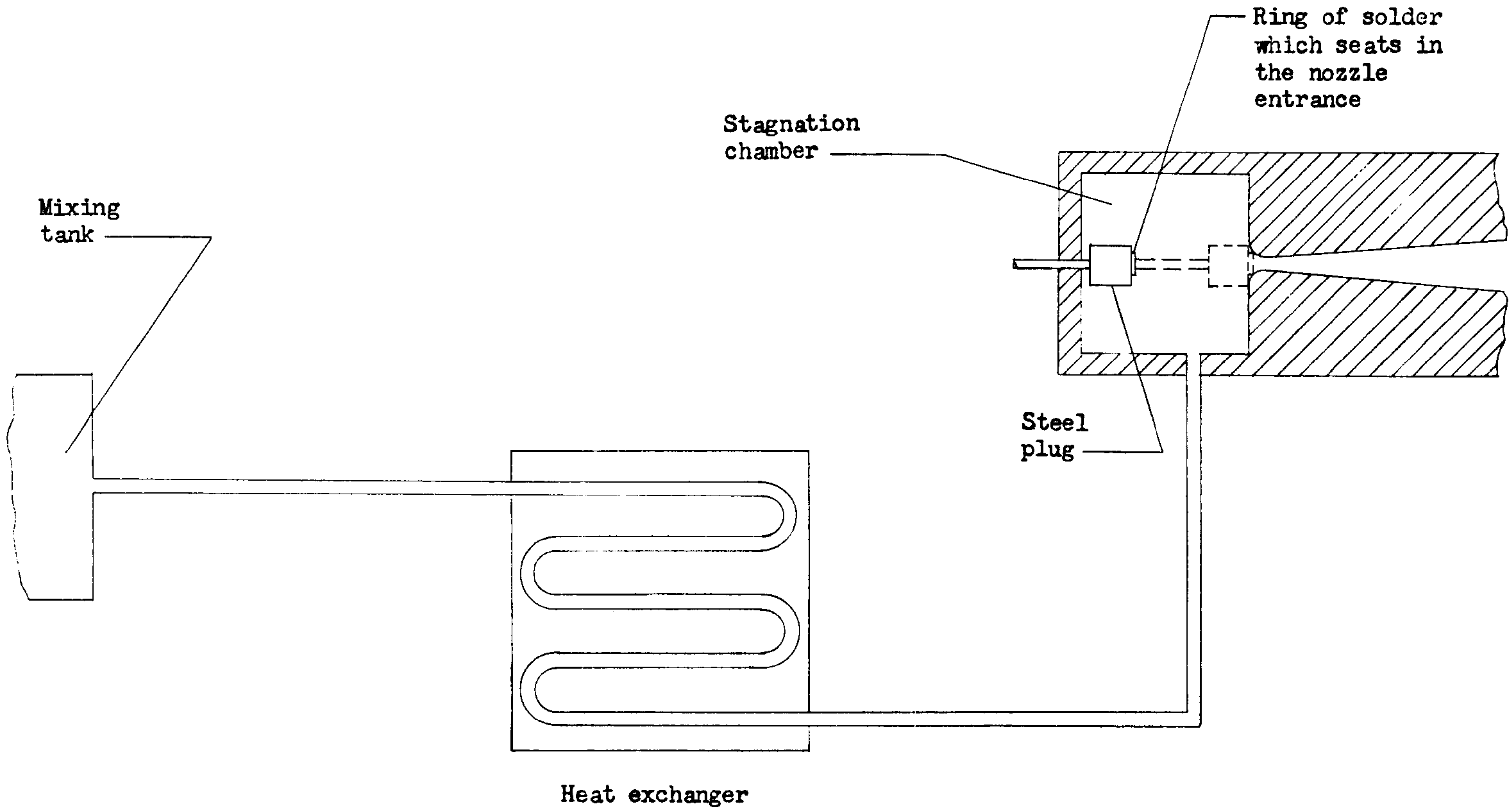


Figure 1.- Portion of static-temperature—static-pressure history of helium as it expands to hypersonic Mach numbers in a nozzle. $p_{t,1}$ = 2,015 lb/sq in. abs; $T_{t,1}$ = 560° R.



(a) General test setup.

Figure 2.- Schematic of test setup.



(b) Diagram of heat-transfer apparatus.

Figure 2.- Concluded.

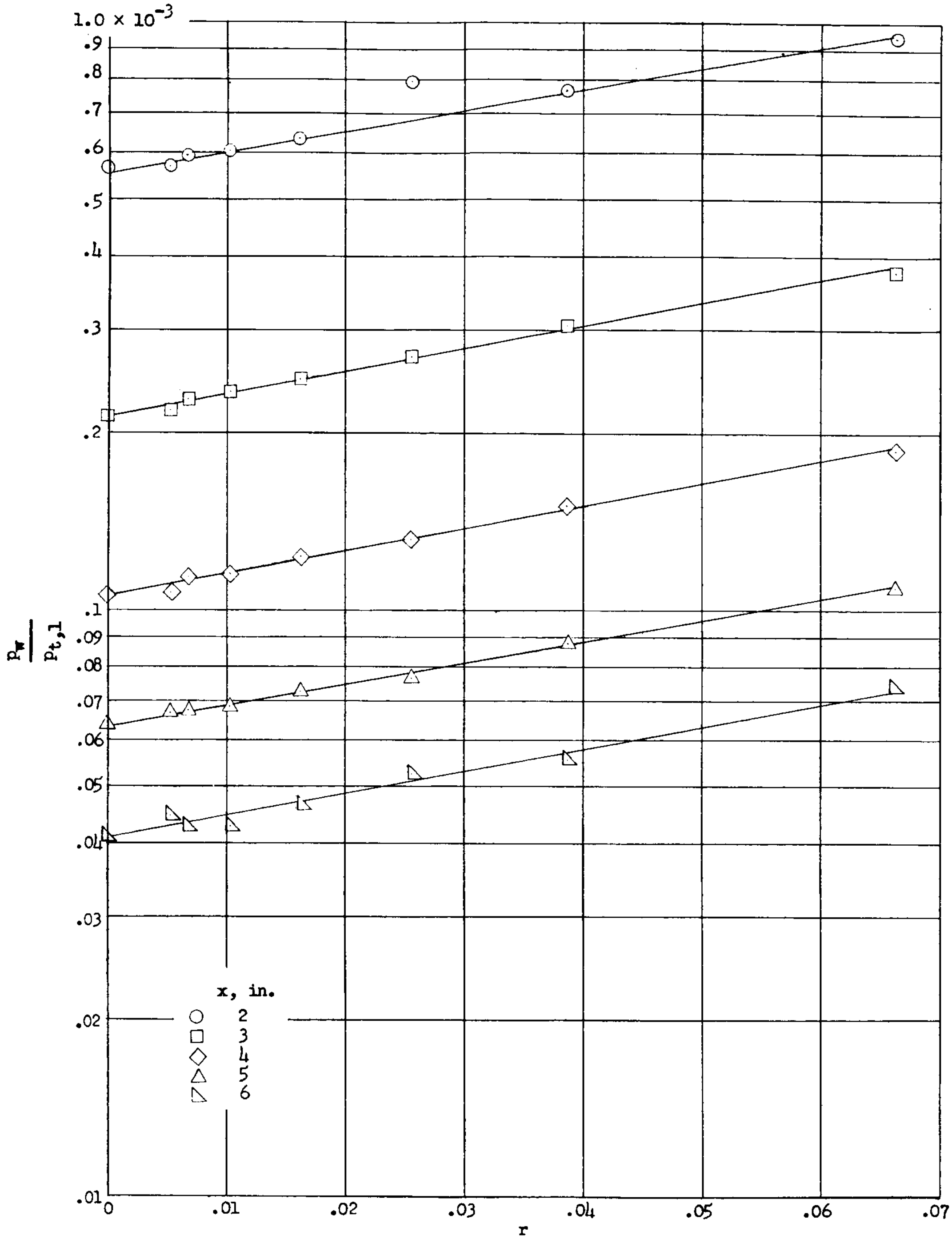


Figure 3.- Variation of wall static-pressure ratio with contamination ratio at tunnel stations $x = 2$ to 6 inches. $p_{t,1} = 1{,}015$ lb/sq in. abs; $T_{t,1} = 540^\circ$ R.

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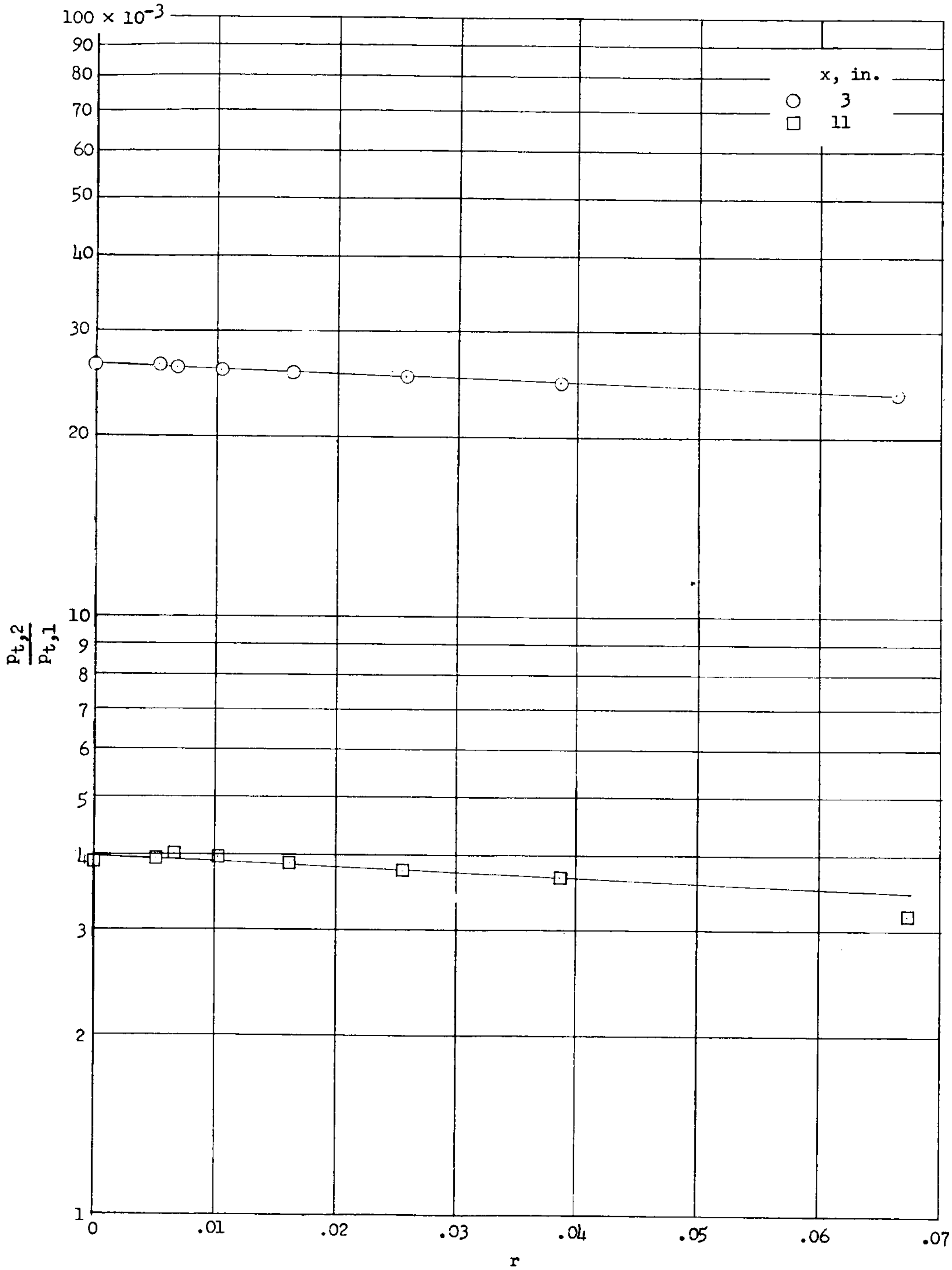

Figure 4.- Variation of center-line pitot-pressure ratio with contamination ratio at tunnel stations x = 3 and 11 inches. $p_{t,1}$ = 1,015 lb/sq in. abs; $T_{t,1}$ = 540° R.

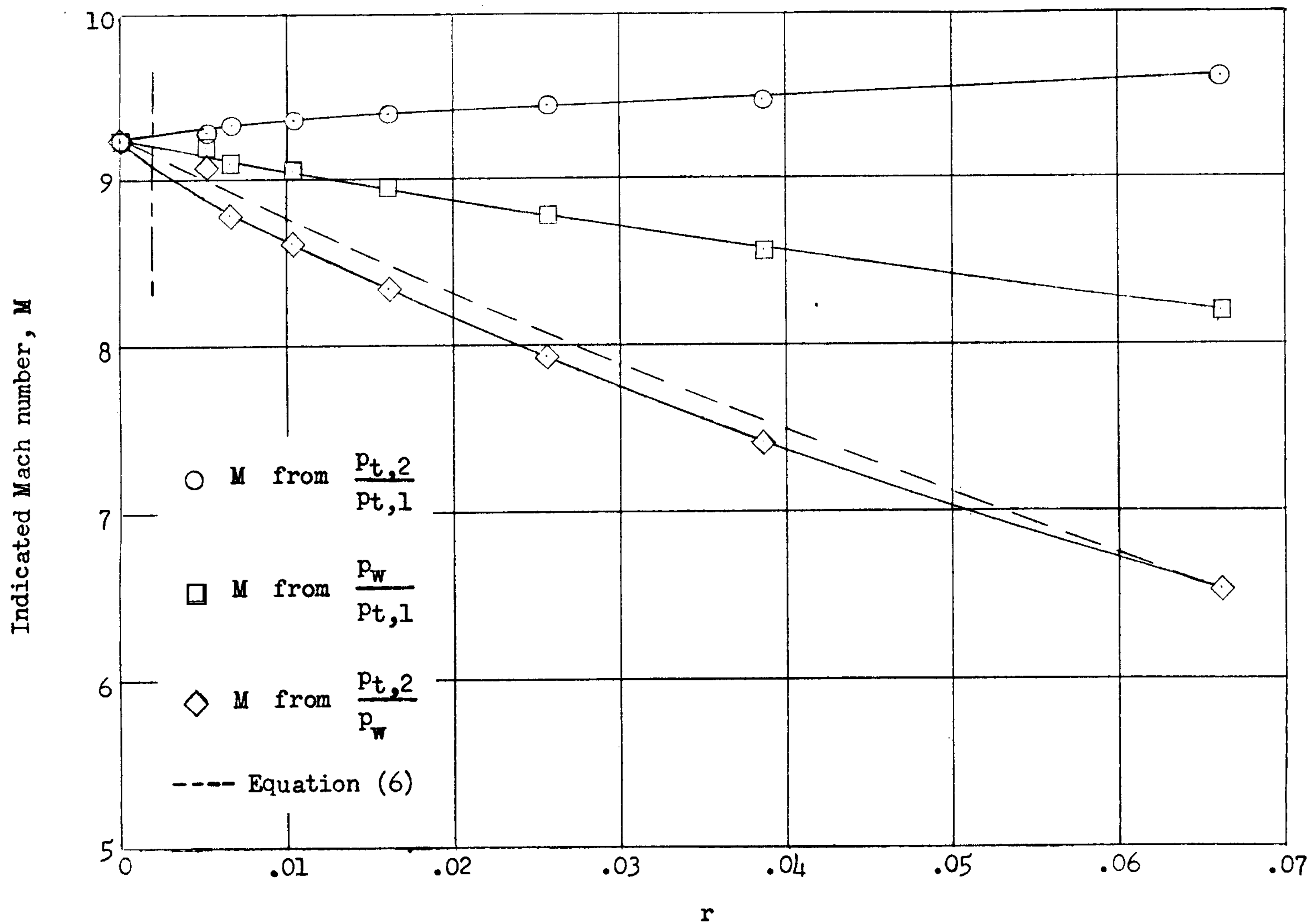

Figure 5.- Variation of the indicated Mach number with contamination ratio at $x = 3$ inches. $p_{t,1} = 1{,}015$ lb/sq in. abs; $T_{t,1} = 540^\circ$ R.

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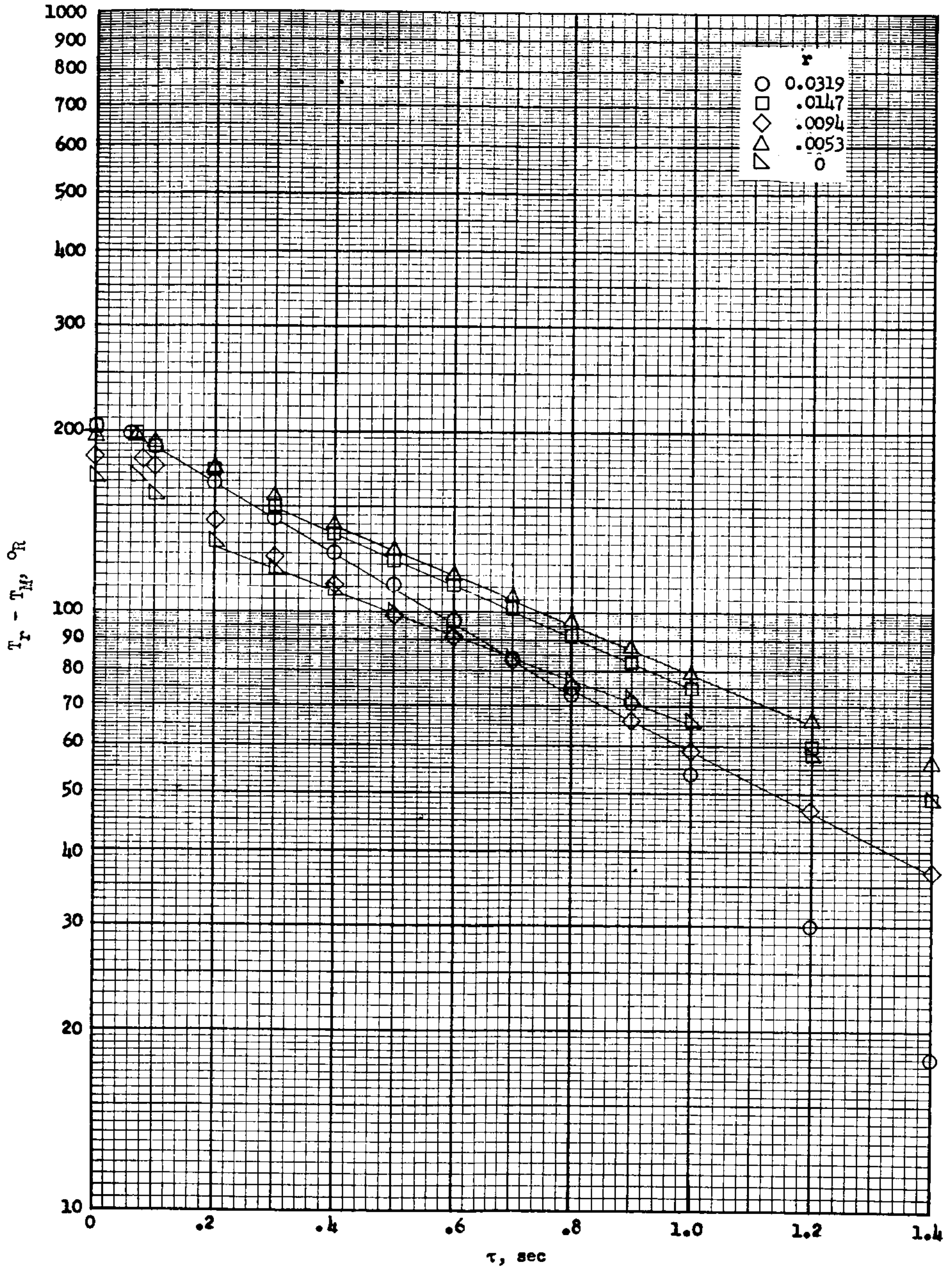
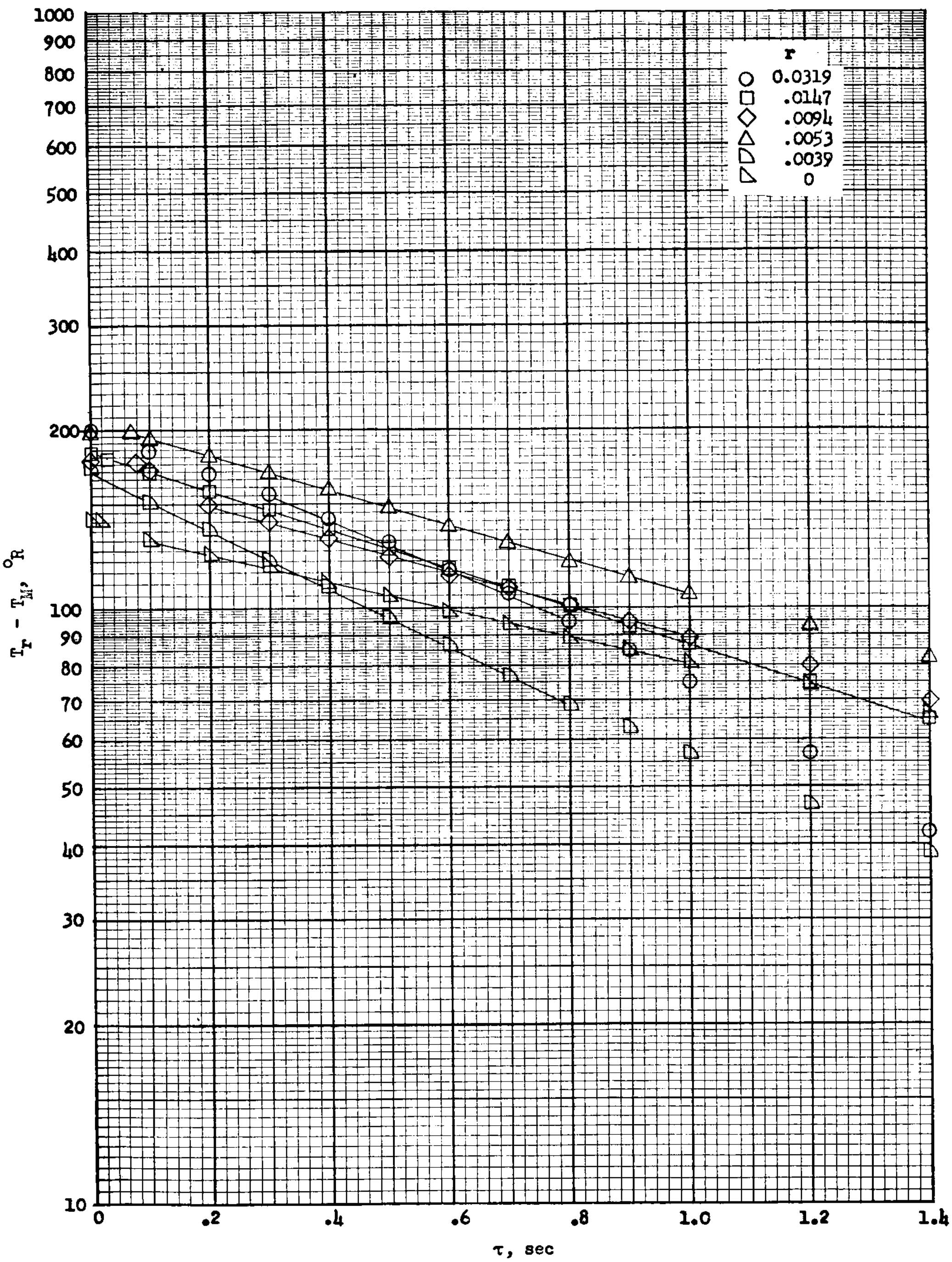


(a) $s/l = 0.259$.

Figure 6.- Variation of the model-wall temperature distribution parameter $(T_r - T_M)$ with time for various contamination-ratio values. $T_{t,1} = 230^\circ$ F; $p_{t,1} = 1{,}515$ lb/sq in. abs; $(M)_{r=0} = 19$.



(b) $s/l = 0.554$.

Figure 6.- Continued.

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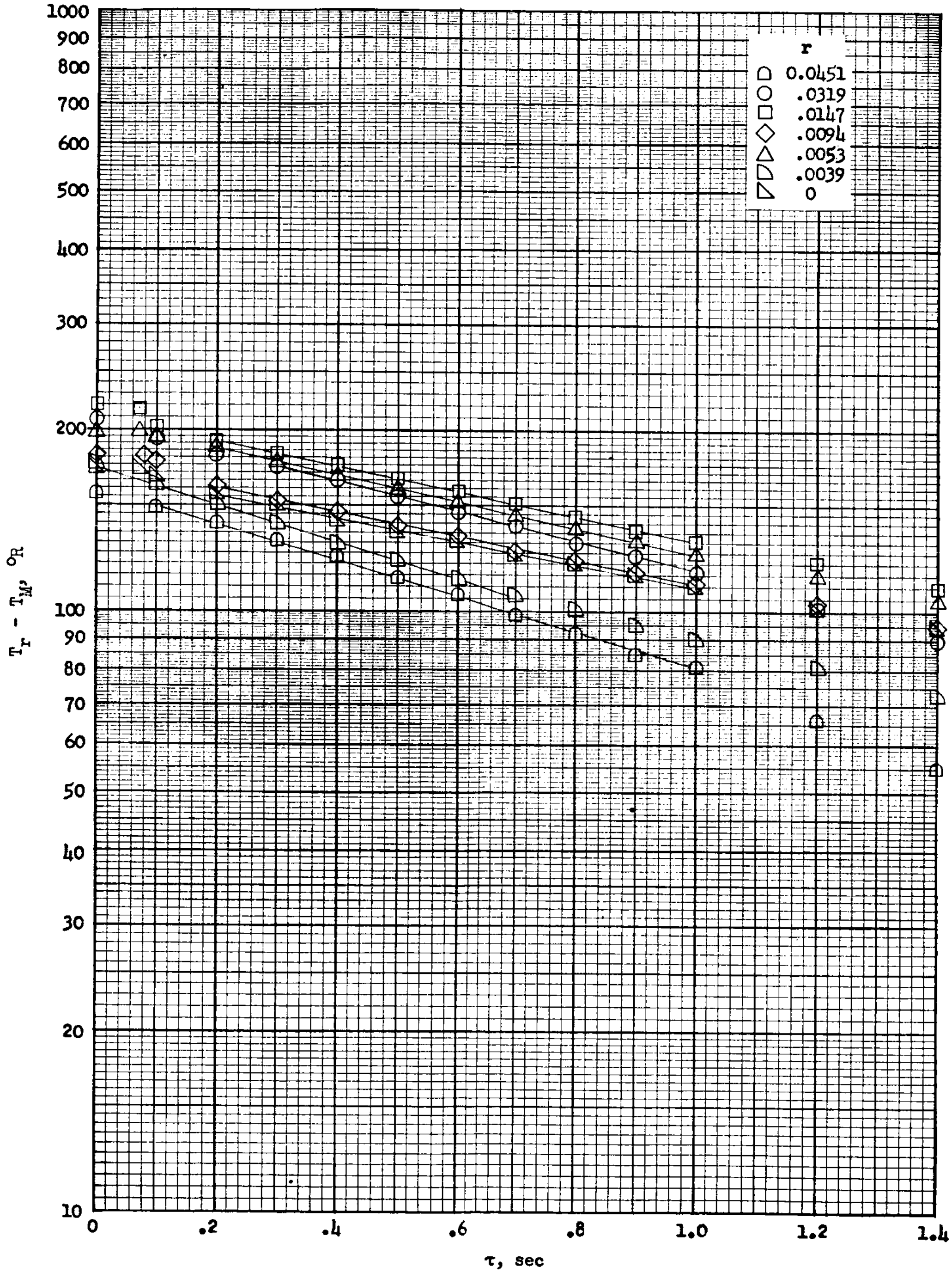
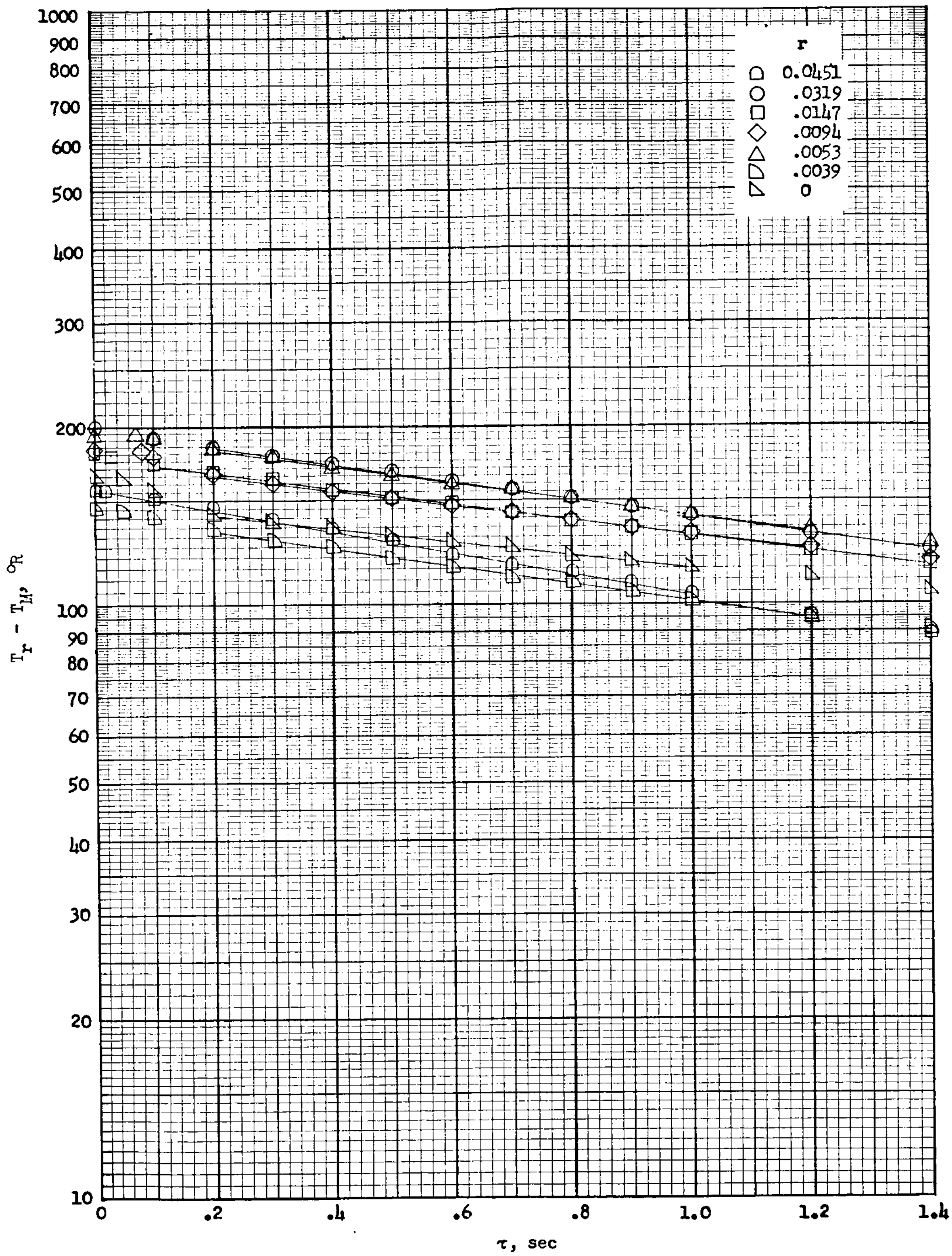


(c) $s/l = 0.782$.

Figure 6.- Continued.



(d) $s/l = 1.005$.

Figure 6.- Concluded.

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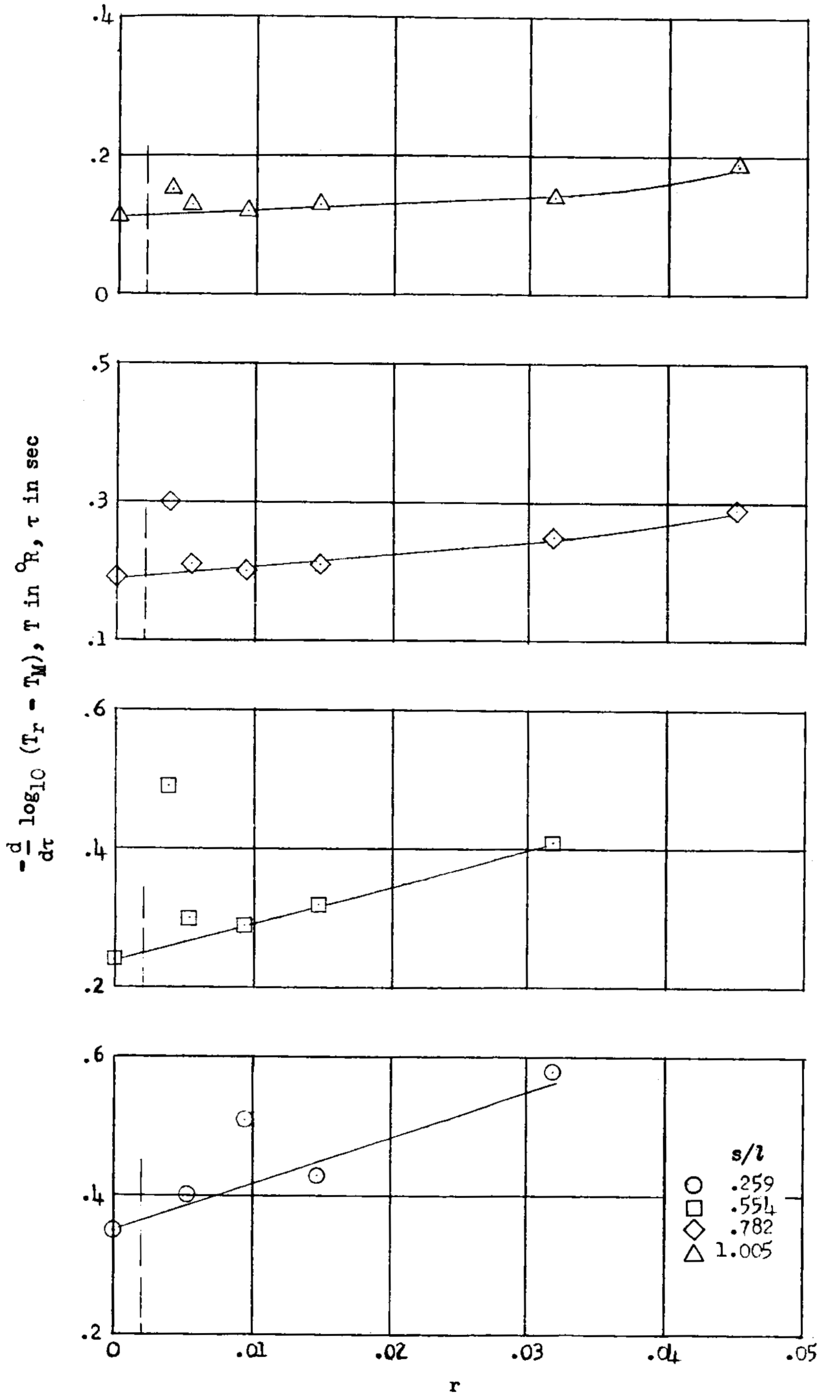

Figure 7.- Variation of model film coefficient of heat-transfer parameter $-d/d\tau \log_{10}\left(T_r - T_M\right)$ with contamination ratio for several body stations.

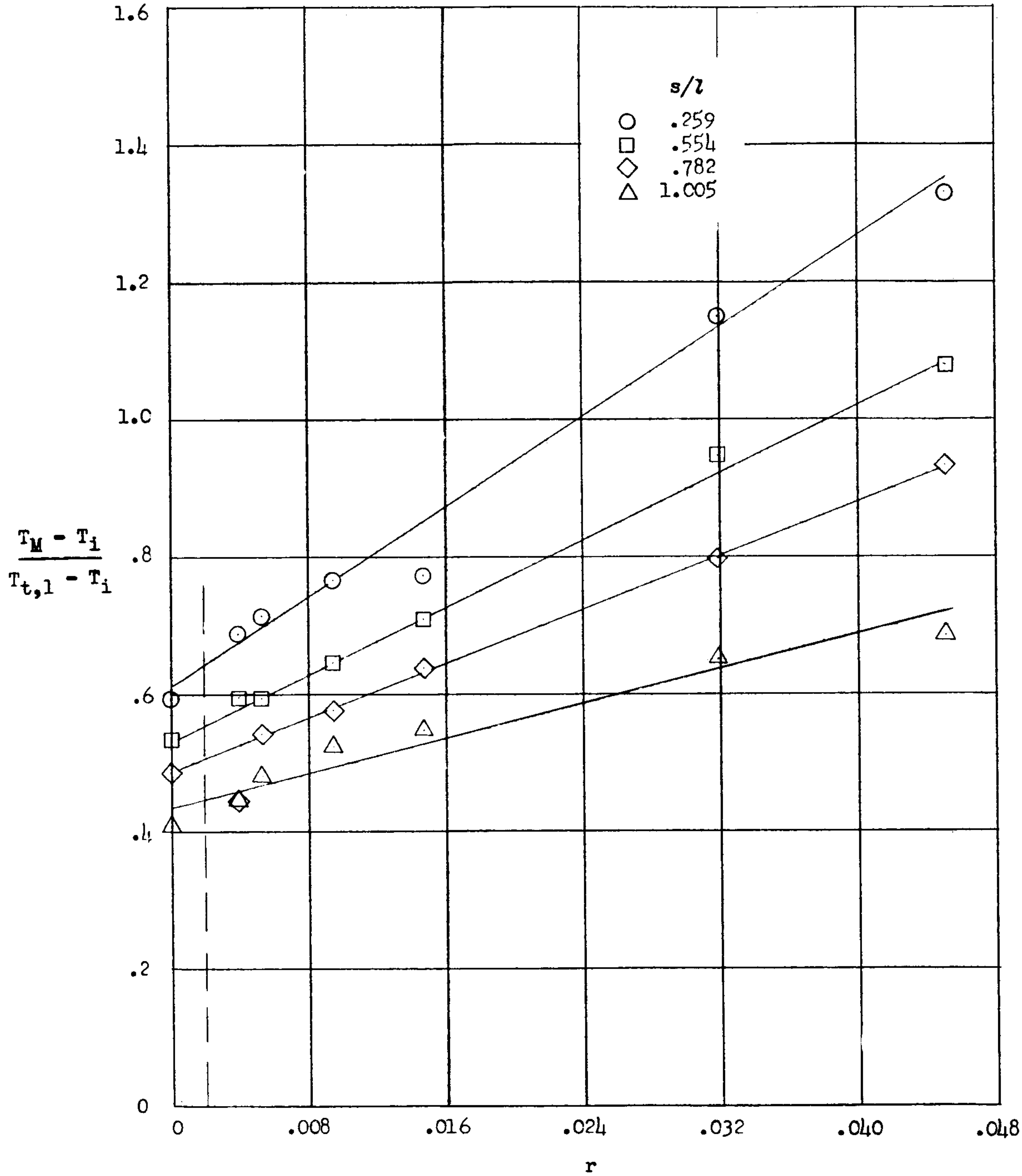

Figure 8.- Variation of model surface-temperature parameter $\frac{T_M - T_i}{T_{t,1} - T_i}$ with contamination ratio r for various stations on 26.6° half-angle cone. τ = 9 sec; $(M)_{r=0}$ = 19.